Electro-optical Modulators and Methods of Modulating Optical Signals

Cross-reference to Related Applications

[0001] This application claims the benefit of priority under 35 U.S.C. § 119 of European Patent Application Serial No.02079871.6 filed on 22 November 2002.

Background of the Invention

Field of the Invention

[0002] This invention relates to electro-optic modulators for use in transmitting or regenerating optical digital signals, and to methods of modulating optical signals in which the modulators of the invention are used.

Technical Background

[0003] Since the refractive index (and in a waveguide structure the effective refractive index) in an electro-optic material can be changed by the application of an electric field (for example by the Pockels effect) or by the absorption of light, it will vary with time according to the modulation wave-form, and this produces changes which can be interpreted as phase modulation or as a change in frequency spectrum, and which are generally referred to as "chirp". In properly designed devices, chirp can be controlled and made use of.

[0004] For example, since the light in optical digital signals cannot be perfectly monochromatic, its transit time through an optical fibre or other transmission path varies sufficiently to produce significant broadening of the digital pulses ("chromatic dispersion") and increases in their rise and/or fall times, ultimately risking that they become indistinguishable and an unacceptable bit-error rate results. If, however, the pulses as originally launched from the transmitter are chirped in a direction opposed to the chromatic dispersion that will arise in the transmission path, the chirping has to be cancelled before pulse broadening will become significant, allowing an increase in the length of transmission path before a regenerator or a repeater must be used.

[0005] In dual-drive modulators, control of chirp is relatively easy to achieve, but in single-drive electro-optical modulators at present known (for example Cartledge, IEEE Photonics Technology Letters, vol 7 no.9, September 1995; and Jiang et al, IEEE Photonics Technology Letters, vol 8 no.10, October 1996, "$LiNbO_3$ Mach-Zehnder Modulators with

Fixed Negative Chirp") adjustment has been limited at most to fine-tuning around a pre-selected chirp level.

SUMMARY OF THE INVENTION

[0006] The present invention provides single-drive electro-optic Mach Zehnder modulators in which chirp can be adjusted over a substantially wider range, so that chirp values can be changed to accommodate planned or unexpected changes in the operating conditions of the optical transmission installation in which the modulators are used, and the need to manufacture and stock multiple types of modulator differing in chirp value is substantially reduced, if not completely eliminated.

[0007] The single-drive electro-optic Mach Zehnder modulator of the invention comprises a body of an electro-optically active material; optical waveguides formed at least partly in that material and constituting a Mach Zehnder interferometer having two limbs constituting alternative light paths between an input and an output so that interference may occur between light taking the alternative paths on recombination at the exit and electrodes for subjecting at least part of at least one of the limbs to an electric field; the interferometer is divided into at least two longitudinally spaced sections with separate sets of electrodes, each said set comprising three (or perhaps four) electrodes for applying corresponding electric fields in a "push-pull" relationship to the corresponding parts of both said limbs, and in at least one said section the waveguides of the two limbs are coupled.

[0008] In some cases, an electrode (but not all of them) may be shared between two (or where applicable more than two) sets; normally this would be used as a ground (earth) electrode.

[0009] In use, a first D C electrical bias will be applied to the set of electrodes in the section where the waveguides are coupled (or one of those sections), and an electrical radio-frequency signal conveying the data to be modulated onto an input continuous-wave light beam will be applied to the electrodes of another section in the usual way, and the invention includes methods of modulating a light signal in which the modulator of the invention is used in this way. If there are only two sections, it will normally be necessary to apply a second D C bias, independent of the first D C bias, to the same electrodes as the radio-frequency signal; if there are three (or more) sections, a D C bias is preferably applied instead to the electrodes of a third section.

[0010] Depending on the chirp effect desired, the said section where the waveguides are coupled, and so the electrodes to which the first D C bias is to be applied may be positioned where such bias will simply serve to adjust the operating point of the modulator (allowing the bias, if any, applied with the data signal to be adjusted to obtain the desired chirp level), in which case the waveguides are preferably coupled throughout their length; or they may be positioned where they will affect the partition of the light between the two limbs (as in a Y-branch variable attenuator) in relative amplitude and relative phase, in which case the associated parts of the waveguides need to be coupled, but other parts are preferably uncoupled. Coupling can be achieved, as is known, by having the waveguides sufficiently close together in relation to their materials and dimensions; for typical waveguides based on lithium niobate diffused with titanium, a spacing (centre to centre) of less than about 28 μm will usually result in a substantial degree of coupling.

[0011] The lengths of the electrodes sets may be chosen, independently of each other, to optimise their particular effects (for example in trading off length and operating voltage).

[0012] The invention can be used with any electro-optic material which can support light guiding: for example, with lithium niobate (z- or x- cut), gallium arsenide and other suitable compound semiconductors, and electro-optic (poled) polymers.

[0013] Additional features and advantages of the invention will be set forth in the detailed description which follows, and in part will be readily apparent to those skilled in the art from that description or recognized by practicing the invention as described herein, including the detailed description which follows, the claims, as well as the appended drawings.

[0014] It is to be understood that both the foregoing general description and the following detailed description present embodiments of the invention, and are intended to provide an overview or framework for understanding the nature and character of the invention as it is claimed. The accompanying drawings are included to provide a further understanding of the invention, and are incorporated into and constitute a part of this specification. The drawings illustrate various embodiments of the invention, and together with the description serve to explain the principles and operations of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] The invention will be further described, by way of example, with reference to the accompanying drawings in which:

Figure 1 is a diagrammatic representation of a first electro-optic Mach Zehnder modulator in accordance with the invention;

Figures 2-4 are graphs to assist understanding of this first modulator;

Figure 5 is a set of simulated eye diagrams for this first modulator;

Figure 6 is a diagrammatic representation of a second electro-optic Mach Zehnder modulator in accordance with the invention;

Figures 7-9 are graphs to assist understanding of modulators of this second type;

Figure 10 is a set of eye diagrams for this second modulator;

Figure 11 is a diagrammatic representation of a third electro-optic Mach Zehnder modulator in accordance with the invention; and

Figure 12-13 are measured graphs to assist understanding of this third modulator.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0016] Reference will now be made in detail to the present preferred embodiments of the invention, examples of which are illustrated in the accompanying drawings. Whenever possible, the same reference numerals will be used throughout the drawings to refer to the same or like parts. Throughout the description of these embodiments, numerical values relate to modulators for use in the 1520-1620 nm waveband; the invention is applicable to other wavebands (in particular the bands around 850 and 1300 nm) but the dimensions will need to be appropriately adjusted.

[0017] The modulator of Figure 1 comprises an x-cut lithium niobate chip 1 in which are formed optical waveguides forming a Mach Zehnder interferometer having an input waveguide 2, parallel limbs 3 and 4 and an output waveguide 3 connected by Y-junctions in the usual way. Each of the limbs 4 and 5 includes an upstream part 6, 7 defining a first section of the modulator, which parts are close enough to each other for a substantial degree of optical coupling to occur between them, and a downstream part 8, 9 defining a second section where the spacing is increased (or alternatively the design of the waveguide could be changed) so that optical coupling between them is negligible.

[0018] In accordance with the invention, a first set of electrodes 10, 11, 12 is formed on the chip in the first section and (since the waveguides are coupled) the voltage or voltages applied to these electrodes influences the relative intensity of light in the two branches and its phase relationship.

[0019] A second set of electrodes 13, 14, 15 defining a second section and optionally a third set of electrodes 16, 17, 18 defining a third section are formed on the chip in a position or positions to apply electric fields to the downstream parts of the waveguides where there is no substantial coupling between the waveguides of the two limbs. A radio-frequency optical signal conveying the data to be modulated onto light passing through the modulator is applied to the electrodes of the second set in the usual way, and a D C bias voltage is applied to the electrodes of the third set, if present, or otherwise also to the electrodes of the second set; the bias voltage is adjusted in the known manner to control the operating point of the interferometer, usually set at the "half-power" point where the response is both steepest and most nearly linear.

[0020] The electrodes 16, 17, 18 of the optional third set (bias electrodes) are shown, by way of example, downstream of the electrodes to which the radio-frequency data signal is applied, but they could alternatively be upstream, or there could be sets of bias electrodes in both these positions, with the same or different bias voltages applied to them. It is also noted that the modulator shown in Figure 1 can be operated with the direction of the light reversed.

[0021] Meantime, adjustment of the voltage (or voltages) applied to the electrodes of the first section allows adjustment of the chirp factor of the modulator, as further discussed below. A useful general discussion of chirp factor can be found in the paper by Koyama et al in *Journal of Lightwave Technology* vol 6 no. 1, January 1988, pages 87-93; note that when used in a quantitative sense, "chirp" is defined by the formula

$$\Delta f = \frac{1}{2\pi}\frac{d\phi}{dt}$$

and "chirp factor" by the formula

$$\alpha = 2P\frac{\frac{d\phi}{dt}}{\frac{dP}{dt}}$$

in which ϕ is the phase of the output light, P is its instantaneous intensity, and t is time.

[0022] The first section of the modulator may be symmetrical between the two waveguides, as shown, in which case a range of positive and negative chirp values is achievable; or it may be made unsymmetrical by adopting different dimensions and/or compositions for the two waveguides, or unsymmetrical locations for the relevant edges of the electrodes, or by applying different voltages to the outer electrodes (10 and 12), or more than one of these, in order to adjust the range of chirp levels achievable. When operating in the 1520-1620 waveband, where standard single-mode fibre has a positive dispersion, it will usually be preferred to use such asymmetry to obtain a range of negative chirp factors.

[0023] Figure 2 shows static extinction ratio (dashed curve) and chirp factor (continuous line) as a function of the coupling constant, and this is also interpreted as the separation between the waveguides for a typical lithium niobate Mach Zehnder modulator with waveguides uniformly 6 μm wide. The relationship between waveguide spacing and coupling coefficient will of course vary depending on the material and other characteristics.

[0024] Figure 3 relates to an interferometer of the type shown in Figure 1 made with x-cut lithium niobate and with waveguides 6.5 μm wide and 3.5 μm deep formed by titanium diffusion, with their axes spaced by 19 μm in the first section and 28 μm in the second section. The electrodes 10, 11, 12 of the first (D C bias) set are 6 mm long and electrodes 13, 14, 15) of the second (R F signal) set 6 mm long, in each case spaced 10 μm apart and symmetrically spaced about the relevant waveguide; optional electrodes 16, 17, 18 are not used. The figure shows the chirp factor obtained with varying voltages applied to the electrode 11 (electrodes 10 and 12 both being earthed (grounded)). This voltage (V) is expressed as its ratio to the voltage (V_π)required on these electrodes to produce a phase change of π, and the chirp ratio is calculated both for small signals (squares, □) and large signals (diamonds, ◇).

[0025] Figure 4 shows the dynamic extinction ratio computed for this modulator when the bias applied to electrodes 16-18 is adjusted to operate at the half-power point (continuous curve) or to maximise the extinction ratio (dotted curve). In either case, a dynamic extinction ratio better than 11dB is achievable over a ±0.5 range of chirp factor. Figure 5 further illustrates the characteristics of this modulator by presenting eye diagrams (for positive and negative slope) of the modulator transfer characteristic in order from the top

down with applied voltages V of zero (chirp factor also zero), $+0.6V_{\pi}$ (chirp factor +0.85) and $-0.6V_{\pi}$ (chirp factor -0.85).

[0026] Figure 6 shows another form of the invention, which is conventional except that the waveguides of the two limbs are close enough to be coupled throughout their lengths. In this type of modulator, the radio-frequency electrical data-input signal and a first D C bias voltage will both be applied to the first set of electrodes 13-15, and a second bias voltage to the second set of electrodes 16-18; the first bias voltage, to a sufficient approximation, sets the chirp factor and the second can be adjusted to obtain the desired operating point condition.

[0027] Figure 7 relates to a symmetrical modulator of this kind in which the spacing of the limbs is uniformly 24 μm, the electrodes 16, 17, 18 6 mm long, and the material and other dimensions as in the previous example. It shows the calculated and observed chirp factor values (dashed and continuous curves respectively) for as a function of the D C bias voltage applied to the first set of electrodes, and also shows (dotted curve) the voltage that needs to be applied to the second set of electrodes to maintain operation at the half-power point (close to a displaced inverse relationship).

[0028] Figure 8 is a corresponding graph for a modified modulator which is made unsymmetric by doubling the width of the gap between electrodes 16 and 17 so that its chirp factor will always be negative; a range of chirp from about -0.4 to -0.6 is obtainable. Figure 9 shows the corresponding simulation results.

[0029] Figure 10 shows eye diagrams for this modulator, the upper one with V_{chirp} set at +2 V and V_{bias} at -0.1V, demonstrating a crossing of 51.2% and an extinction ratio of 14 dB, and the lower one with V_{chirp} set at -4 V and V_{bias} at -3V, demonstrating a crossing of 49.6% and an extinction ratio again of 14 dB.

[0030] Figure 11 shows another design of modulator in accordance with the invention which is similar to the one shown in Figure 6 but with the addition of a further set of electrodes 19-21 defining a third section upstream of electrodes 13-15; by applying a further D C bias to these, while the R F data signal is applied to electrodes 13-15 and another D C bias to electrodes 16-18, it becomes easier to achieve a desired chirp value and at the same time maintain the desired operating conditions.

[0031] Figures 12 and 13 are graphs computed for a modulator in accordance with Figure 11 which is identical to the one to which figures 6-10 relate apart from the addition of the set of electrodes 19, 20, 21, which are 6 mm long. They show as a continuous curve the chirp factor as a function of the voltage applied to these upstream electrodes 19-21 and as a dashed curve the voltage that needs to be applied to the second set of electrodes 16, 17, 18 to maintain operation at the half-power point. Figures 12 and 13 are measured for operating wavelengths of 1550 nm and 1610 nm respectively.

[0032] It should be noted that the invention is applicable in communication systems using either RZ or NRZ formats, and that it requires no additional radio-frequency electronics.

[0033] It will be apparent to those skilled in the art that various modifications and variations can be made to the present invention without departing from the spirit and scope of the invention. Thus it is intended that the present invention cover the modifications and variations of this invention provided they come within the scope of the appended claims and their equivalents.